Mineralogy and space weathering found in the fine-grained samples returned from the C-type asteroid Ryugu

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Introduction: The JAXA Hayabusa2 spacecraft returned samples from near-Earth C-type asteroid Ryugu. Our Hayabusa2-initial-analysis Min-Pet Fine ("Sand") team has investigated mineralogy and petrology and space weathering of grains in the fine-grained fraction of the samples. Space weathering is alteration induced mainly by solar wind irradiation and micrometeoroid impact. Here, we report the mineralogy, microstructural, and chemical features related to space weathering of the Ryugu grains.

Samples and Methods: Surface morphologies of ~700 grains were observed by field emission scanning electron microscopy (FE-SEM) at Kyoto University and focused ion beam (FIB)-SEM at Kyushu University. Thin foil samples were prepared by FIB-SEM at both universities. A polished sample of a fragment originating from a large grain A0058 (~3 mm wide), which was allocated to the Hayabusa2-initial-analysis Chemistry team, was also investigated. We performed transmission electron microscopy (TEM), synchrotron radiation X-ray absorption fine structure (XANES and EXAFS) spectroscopy, nanotomography, and atom probe analysis at 16 universities and laboratories spread across the world. In addition, more than 200 grains are being investigated until the end of the period of the initial analysis.

Results and discussion: Mineralogy of fine-grained fraction of the Ryugu samples. Major minerals of the small Ryugu grains are saponite, serpentine, Fe-Ni sulfides, magnetite, dolomite, and breunnerite. The mineralogy and petrology of the Ryugu FIB sections investigated are similar to CI chondrites, but the samples lack ferrihydrite and sulfates, commonly found in CI chondrites [1]. Considering the effects of terrestrial weathering of CI chondrites, we infer that the mineralogy of investigated Ryugu grains represents that of CI chondrites prior to their weathering upon arrival on Earth.

Space weathering of Ryugu samples. Recognizable surface modifications of the phyllosilicate-rich matrix were found on 6 to 7% of the observed grains. A variety of surface modifications are observed: melt splashes, amorphous layers, and melt layers. The amorphous layers form a continuous sheet ~0.1 µm thick composed of amorphous silicate material at the top surface. Their bulk chemical compositions are indistinguishable from those of the underlying phyllosilicate-rich matrix, but they have a higher ratio of Fe^{2+} relative to Fe^{3+} than the interior phyllosilicate-rich matrix. The melt layers have bubbles and numerous submicroscopic (<100 nm) rounded Fe-Ni sulfide beads. These data suggest that both silicate and Fe-Ni sulfides were melted and immiscibly separated into silicate and sulfide melts. Such melt layers have higher Fe and lower Si+Al and Mg ratios, as well as a higher ratio of Fe^{2+} relative to Fe^{3+} than the interior phyllosilicate-rich matrix.

The surface morphology of the amorphous layers resembles the surface of an experimental product of Orgueil CI chondrite that was irradiated by 4 keV He^{+}. To a first approximation, it appears that solar-wind irradiation likely played an important role in modifying the surface of the phyllosilicate-rich matrix. Structures of the melt layers resemble those of the products from the laser irradiation

experiments that simulate micrometeoroid impacts [2], suggesting that they had an important role in forming the melt layers. Only a small amount of nanophase (np) Fe^0 was formed on the surface of the melt layer, which may be related to the high relative abundances of Fe^{3+} to Fe^{2+} in Ryugu grains compared to Itokawa and lunar grains. The H_2O in phyllosilicates may also be responsible for this difference.

Given the assumptions that solar wind irradiation is rapid and that micrometeoroid impact processing is slow [3], Ryugu grains preserve a range of stages of space weathering. Some have a melt layer that covers an amorphous layer, others show the effects of multiple micrometeoroid impact. Furthermore, some have blisters (bubbles formed near the surface) on the surface of a melt layer. These multiple space weathering textures suggest that effects of solar wind irradiation accumulate rapidly and the effects of micrometeoroid impact overprint later. In some cases, solar wind gaseous species implanted on the surface of a melt layer and later micrometeoroid impact heating may have induced formation of blisters on the surface. Of course, the natural overturn or gardening of regolith grains on the asteroid parent body interrupts these stages so that the weathering process on any single grain does not necessarily progress linearly.

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